Testing GR on cosmological scales with weak gravitational lensing

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Fermilab

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Agenda

- Weak gravitational lensing –

  what, how, and why

- The “parameterized post-Friedmannian” framework –

  model-independent constraints on modified gravity from weak lensing

- The High Altitude Lensing Observatory –

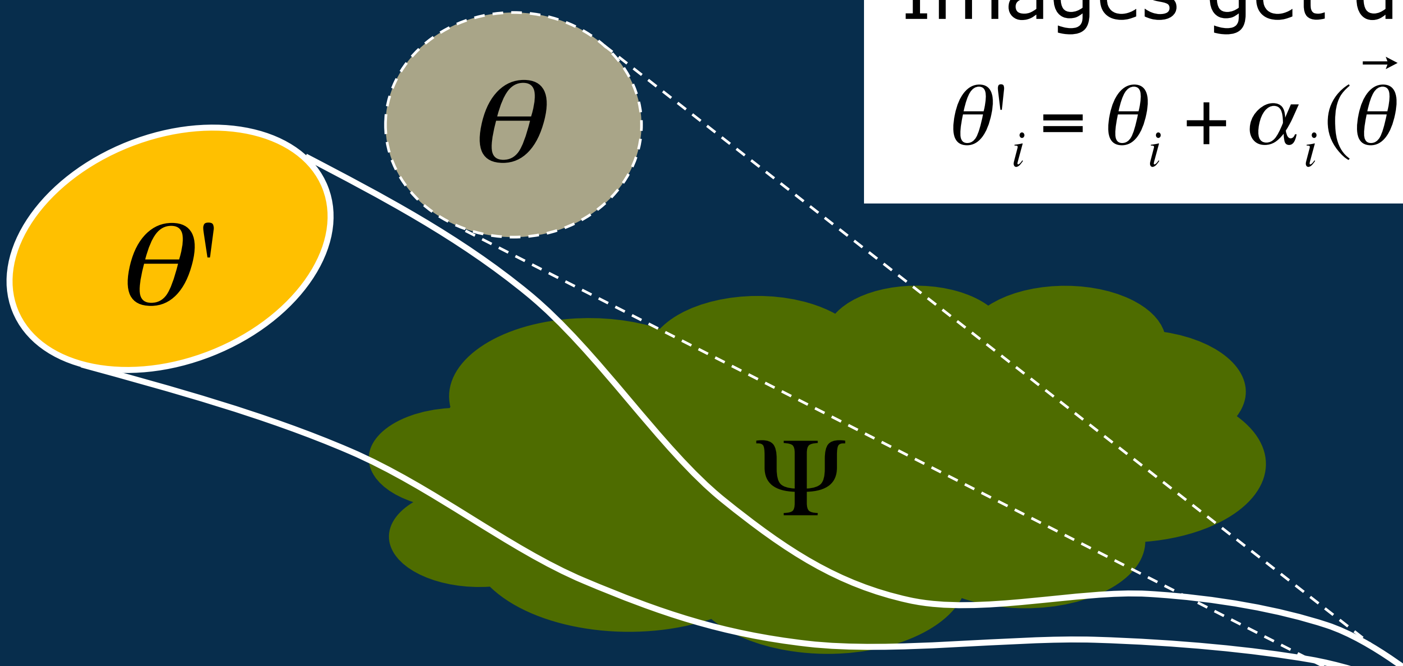
  a new concept for a balloon-borne weak lensing survey

Weak lensing

Matter acts like a lens

Images get distorted:

$$\theta'_i = \theta_i + \alpha_i(\vec{\theta}) = A_{ij}\theta_j$$

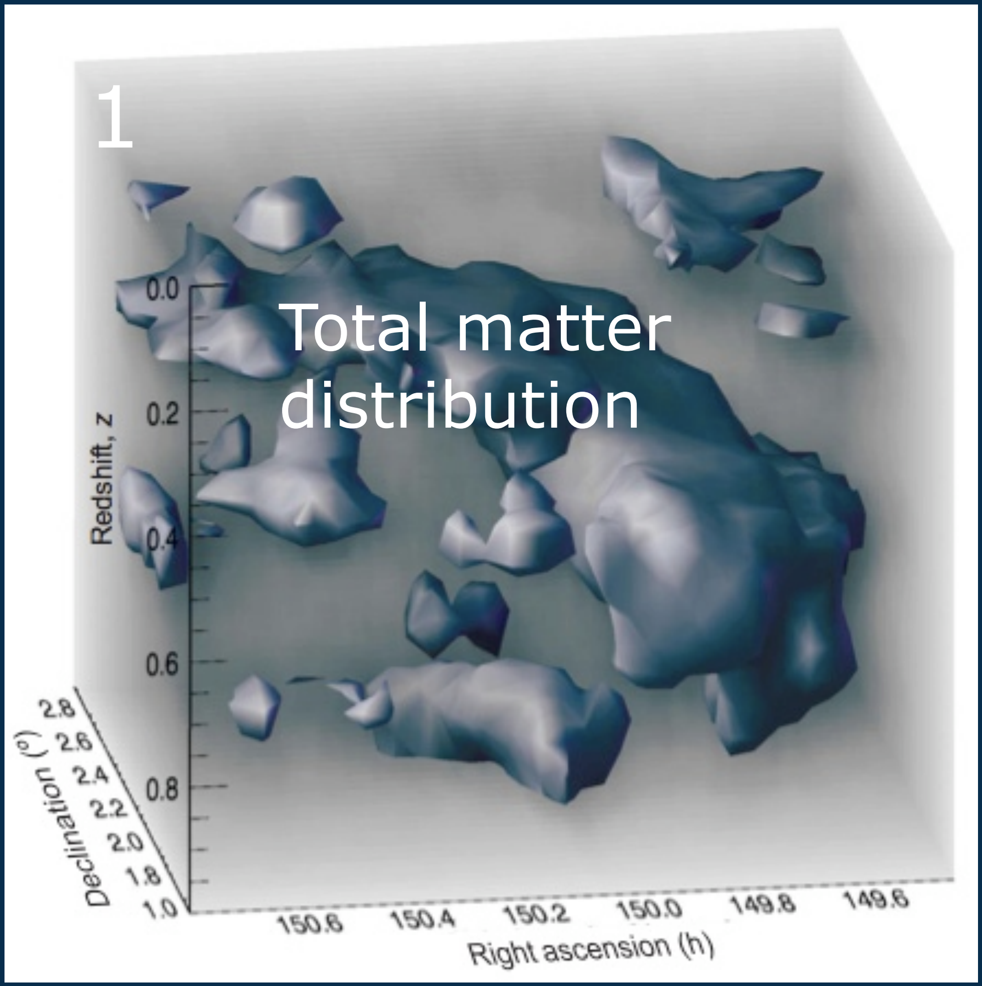


$$A_{ij} = \delta_{ij} + \frac{\partial^2 \Psi}{\partial\theta^i \partial\theta^j}\ *$$

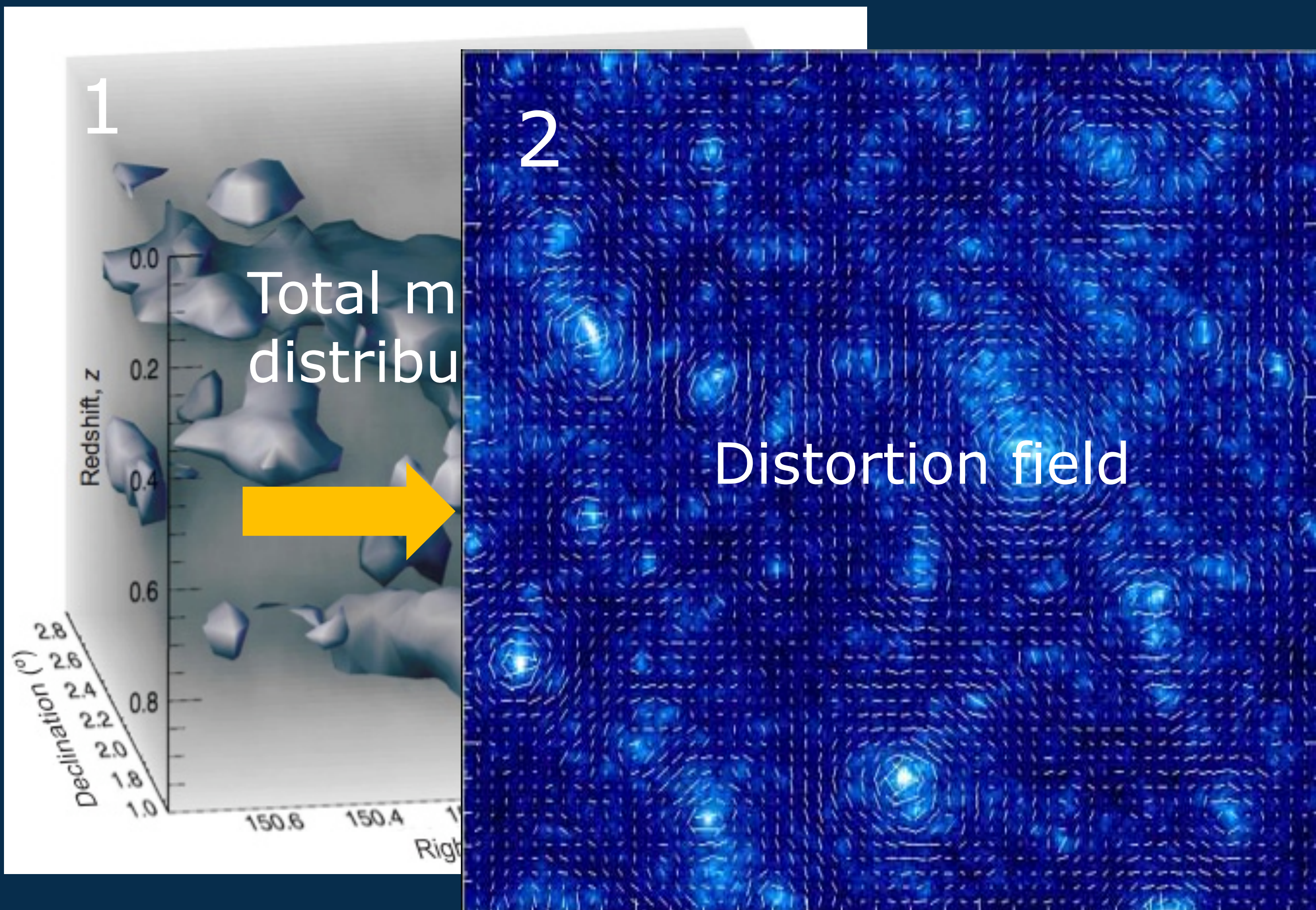
* In GR, to linear order

Why should we care?

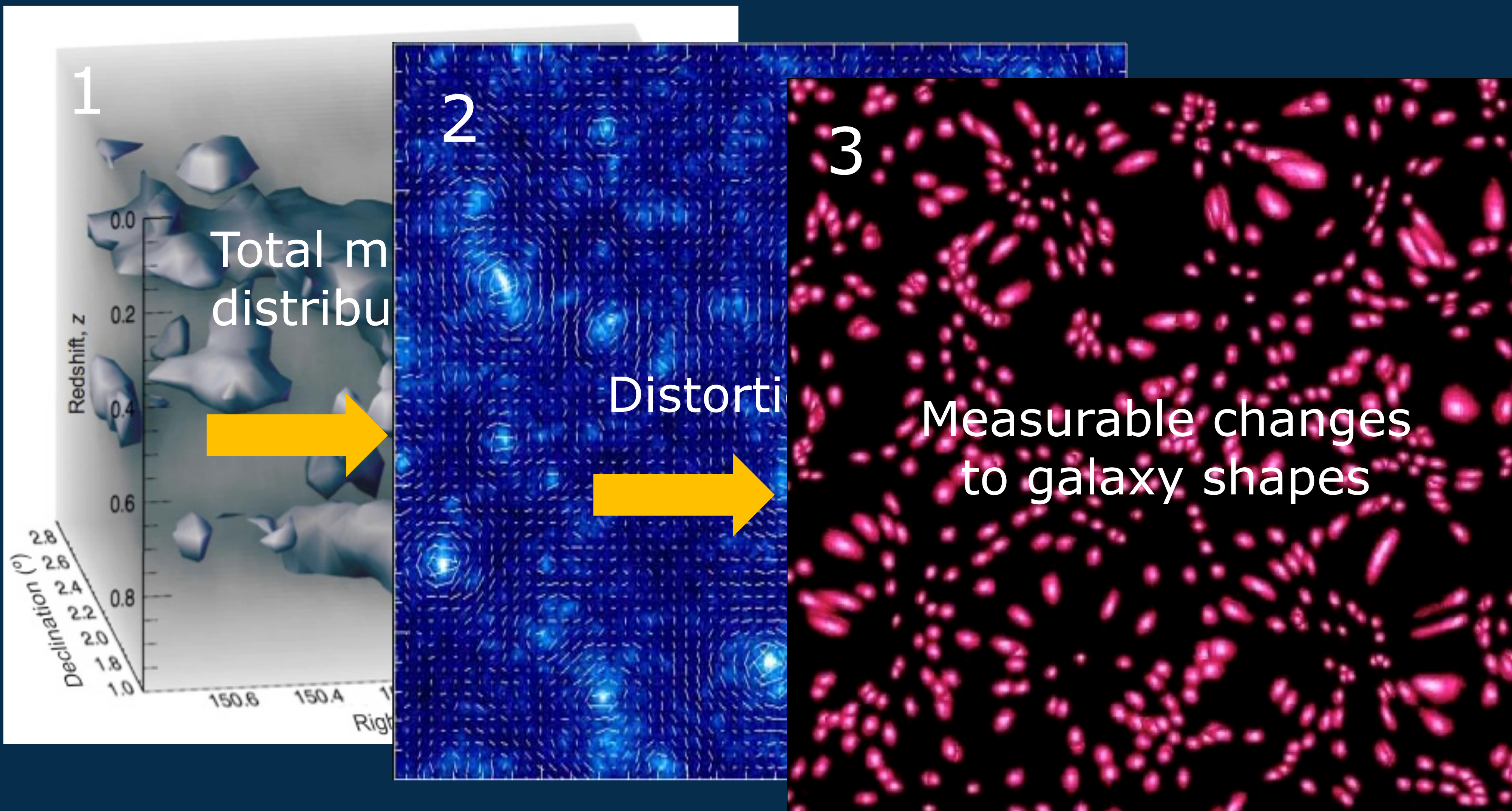
From matter distribution to galaxy distortions



From matter distribution to galaxy distortions

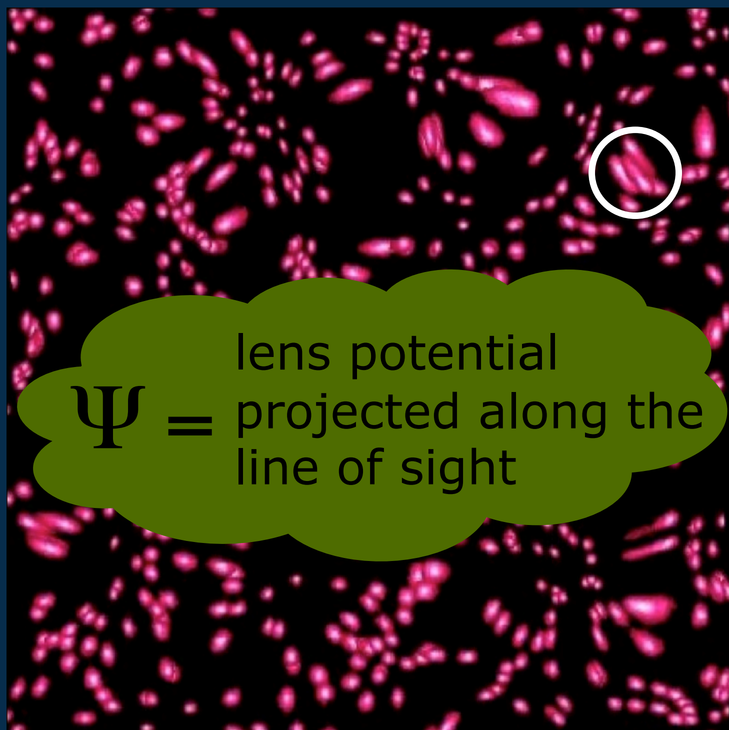


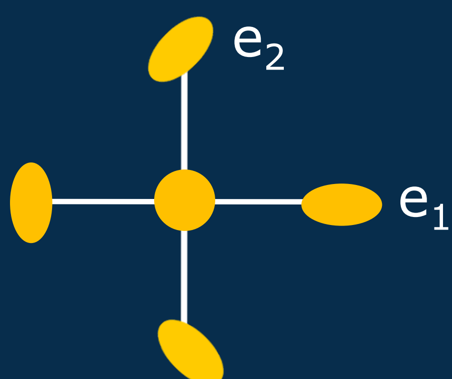
From matter distribution to galaxy distortions



Goal –
to unravel this process to get from 3 back to 1

From galaxy shapes to matter distribution





Galaxy ellipticity is an estimator of the shear:

$$\langle e_i \rangle \approx 2\gamma_i$$

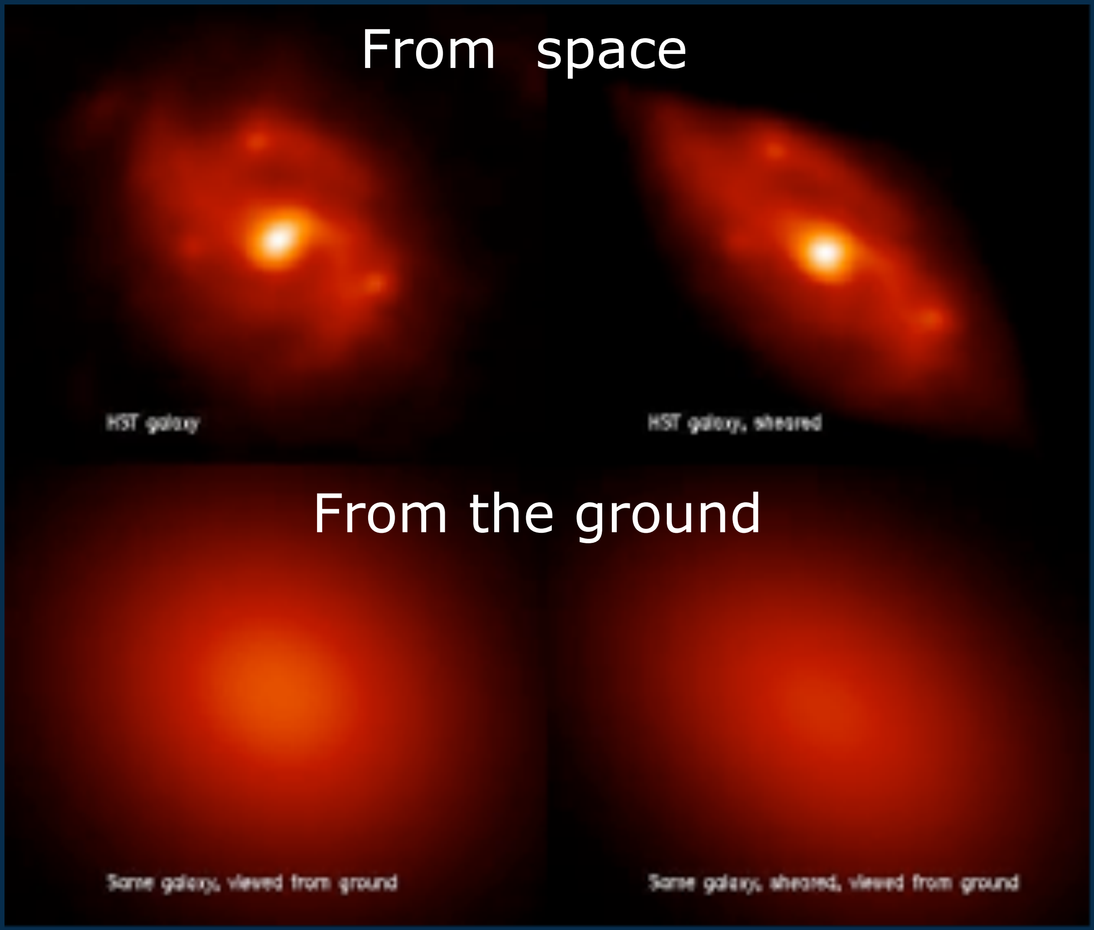
The shear is a component of the distortion tensor:

$$A_{ij} = \delta_{ij} + \frac{\partial^2 \Psi}{\partial \theta^i \partial \theta^j}$$

$$\equiv \begin{pmatrix} 1+\kappa+\gamma_1 & \gamma_2 \\ \gamma_2 & 1+\kappa-\gamma_1 \end{pmatrix}$$

Why this is hard

Many other effects distort galaxy shapes and mimic the lensing signal we are trying to extract:

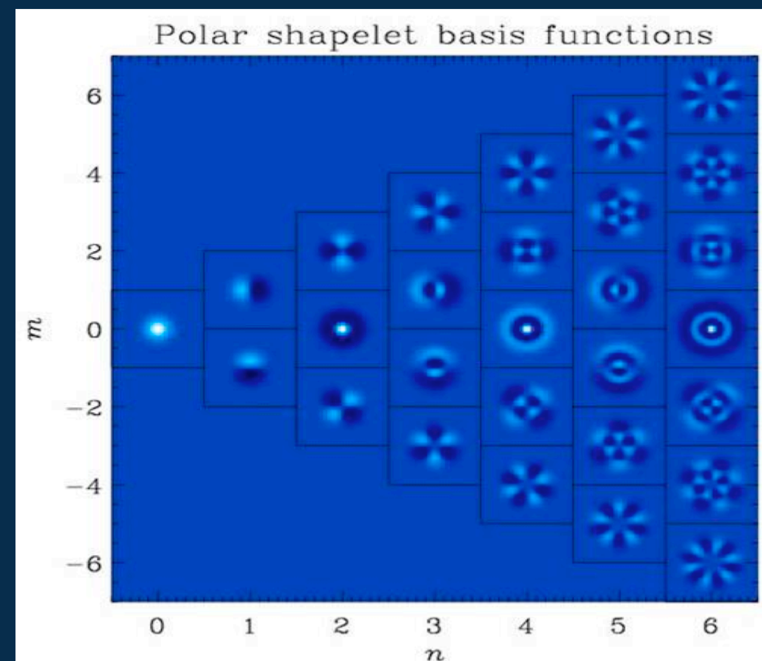


- Atmospheric seeing
- Intrinsic alignments (Hirata & Seljak 2004)
- Instrumental point spread function
- Detector effects, e.g. pixelization and charge transfer inefficiency (Massey et al. 2009)
- Lossy data compression*

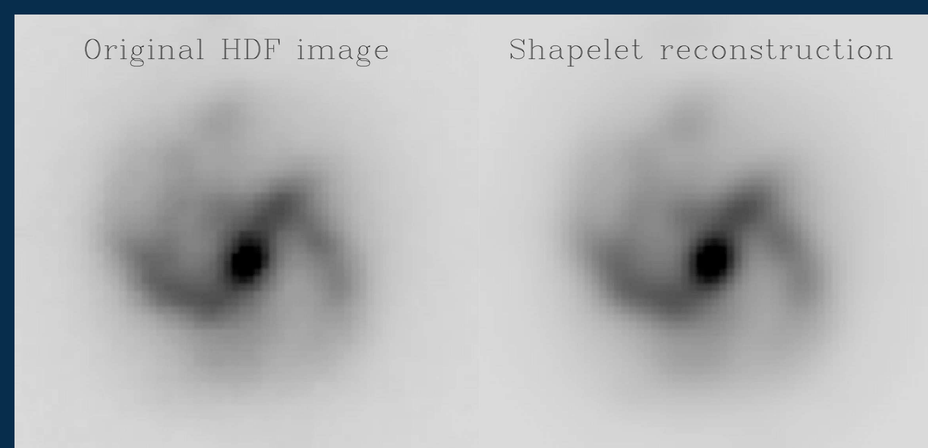
Survey simulations

Weak lensing image simulation housed @ Caltech (Dobke et al. in prep)

- Galaxies based on Hubble UDF
- Realistic shapes modeled with *shapelets*



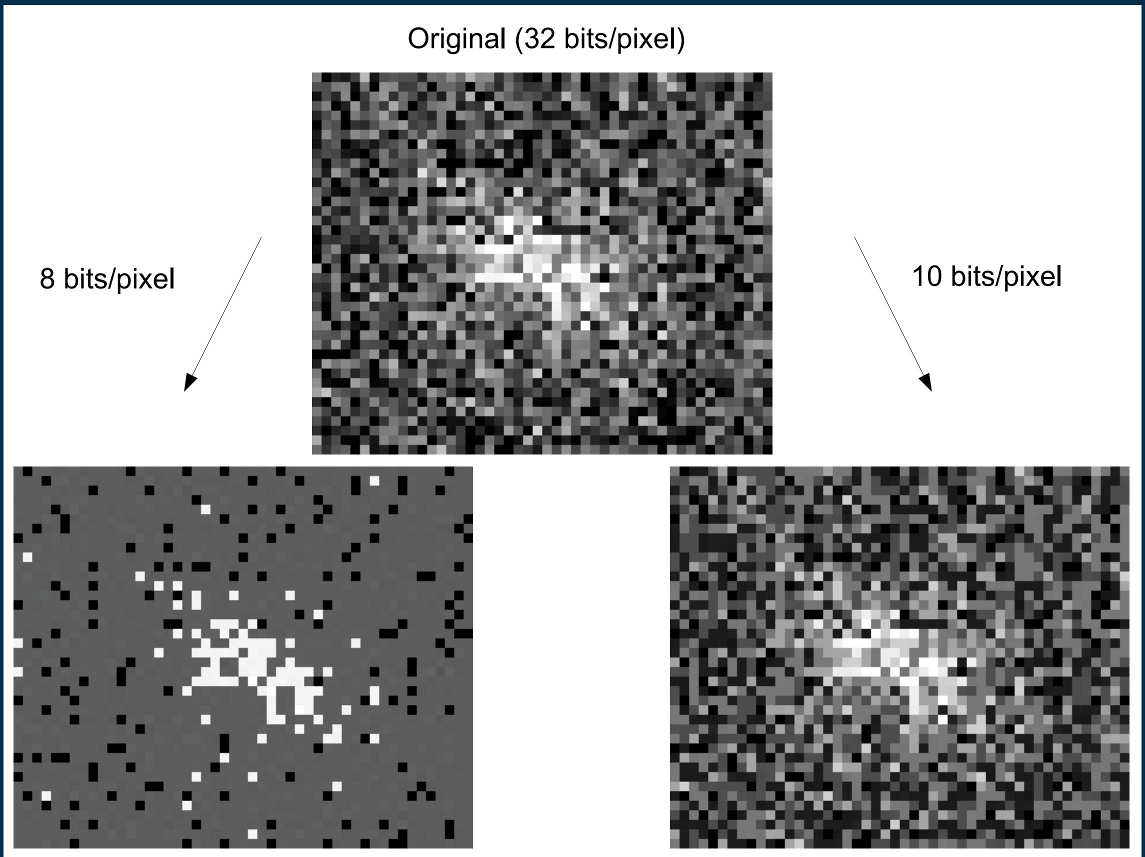
Parameter file input:	Description:
throughput_ratio	Total system throughputs relative to UDF
pixel_scale	The instrument pixel scale in arcsecond/pixel
read_noise	CCD read noise in number of electrons
psf_type	Selects which PSF (UDF etc.) to use
collecting_area	The mirror collecting area in m^2
band_begin	The band on which to start the simulations
band_end	The band on which to end the simulations
exposure_time	Exposure time in seconds
area	The area on the sky to simulate in sq. arcmins
random_seed	A random seed for all random selections
gamma	The user specified weak lensing shear
output_file_pref	Selection of output image file names
n_star	Number of field stars to be added
n_gal	Number of field galaxies
filter_files	Path to user's transition filter files
ee50	The half light radius of the PSF



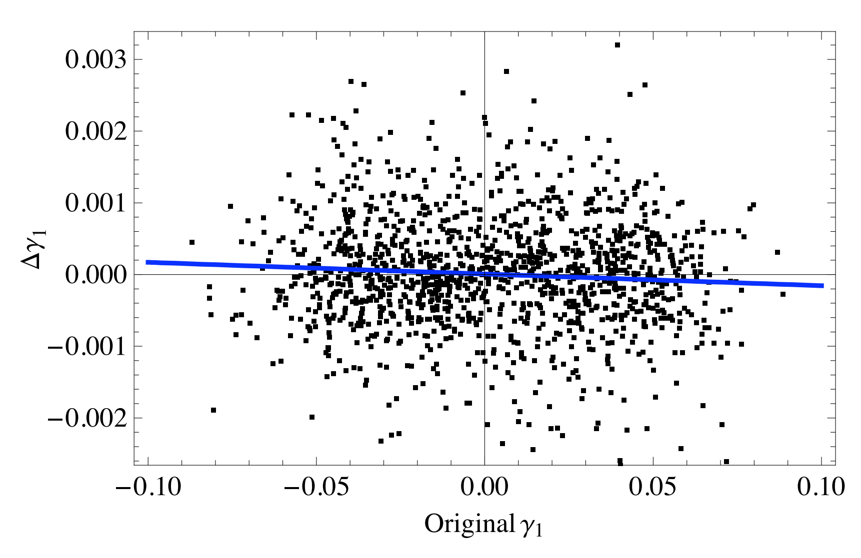
Example: Lossy data compression

Next-generation space missions may produce data faster than our networks can handle

→ lossy data compression?

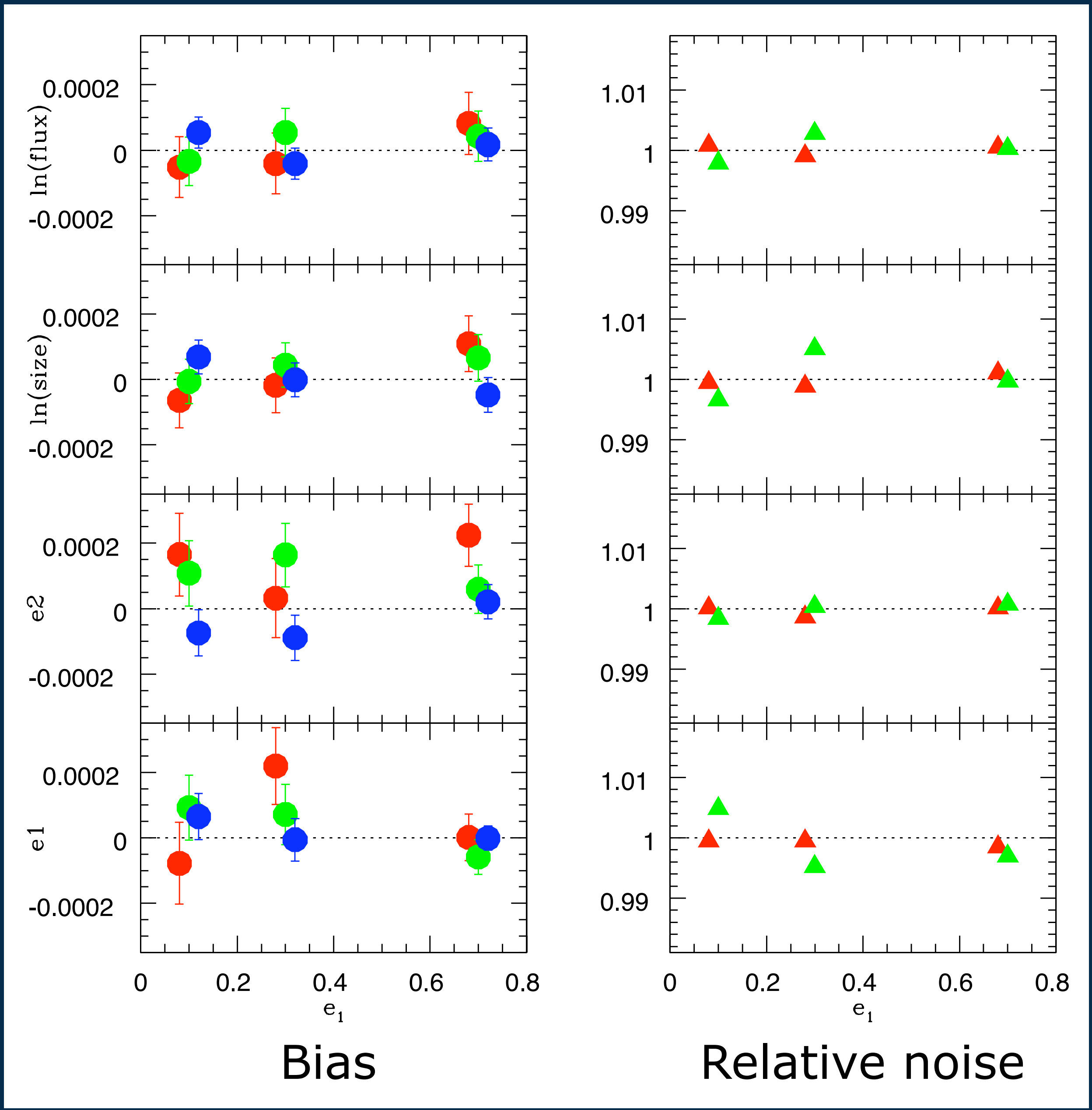


$$x' = Int(0.5 + A + \sqrt{Bx - C})$$



Systematic bias? Extra noise?

How large is the effect?



Simulated images of galaxies with exponential profiles:

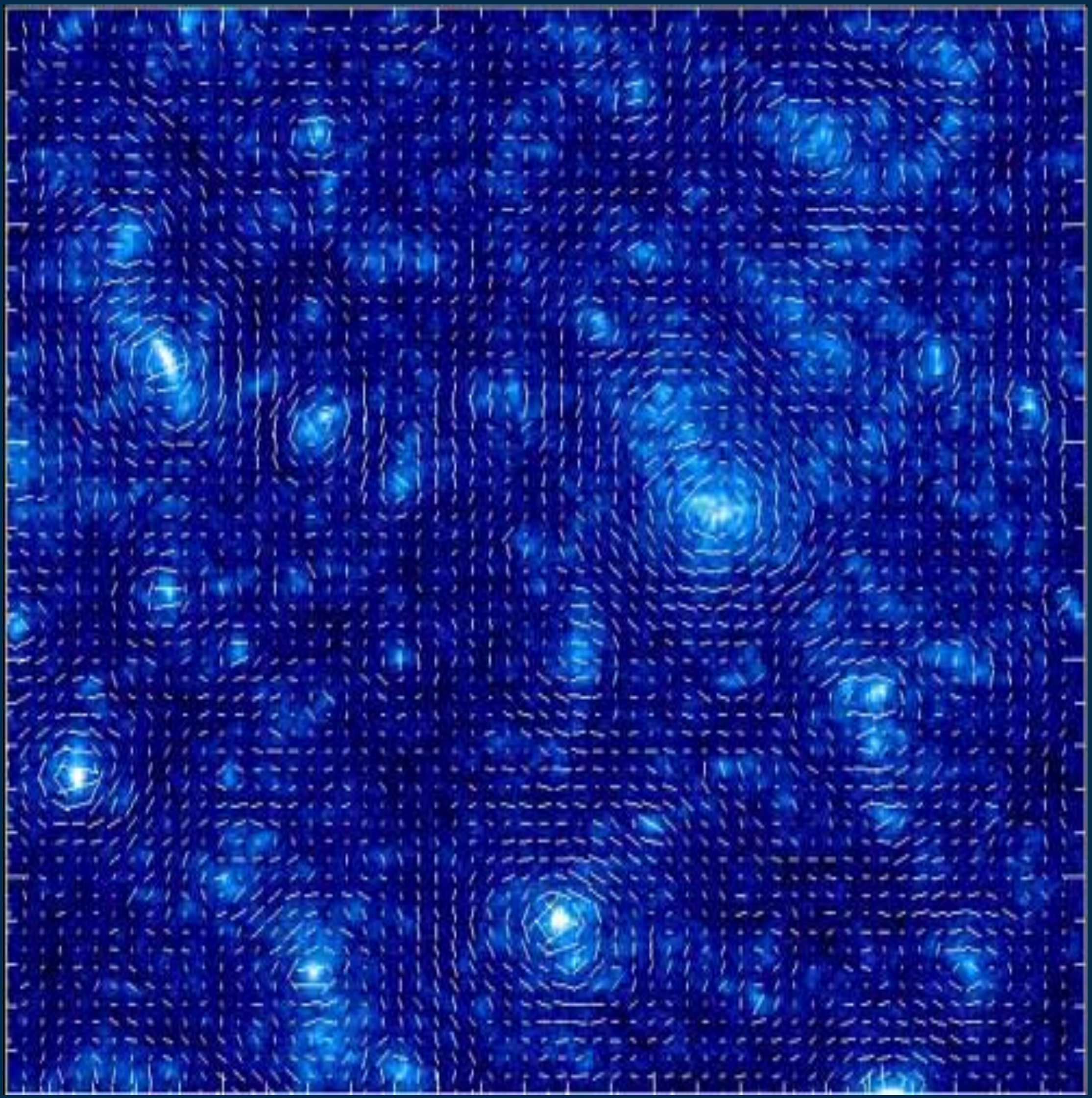
Bias ≤ 10^{-4}
Noise ≤ 1%

(Bernstein et al. in prep)

Results from shapelets simulation on JPL supercomputer soon

(AV et al. in prep)

Weak lensing science

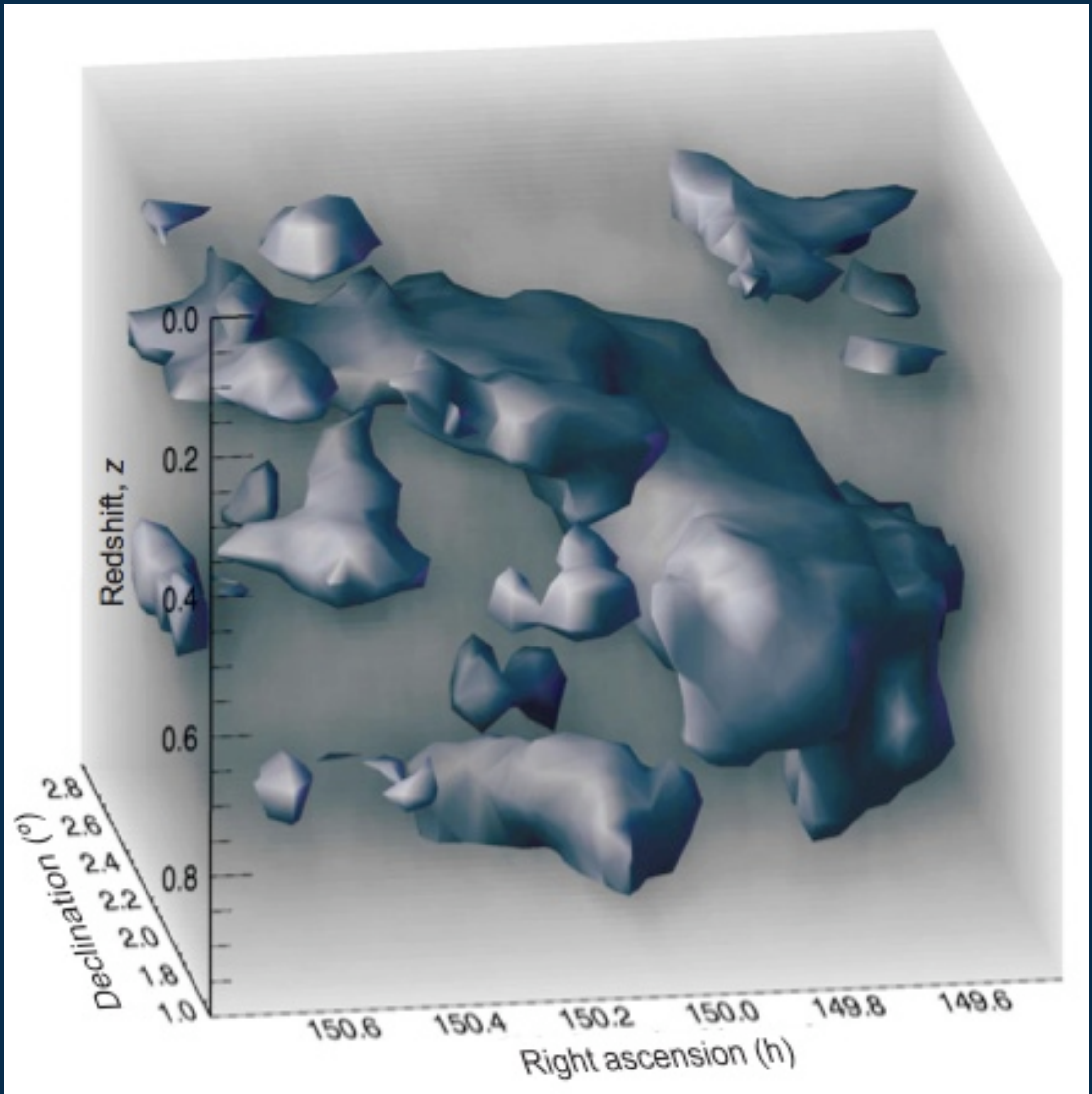


Numerical simulation (Jain, Seljak & White 2000)

The shear map (with redshifts) and its statistics tell us about:

- the large scale matter distribution
- the evolution of large scale structure
- other cosmological parameters
- non-Gaussianity
- etc…

Dark matter maps

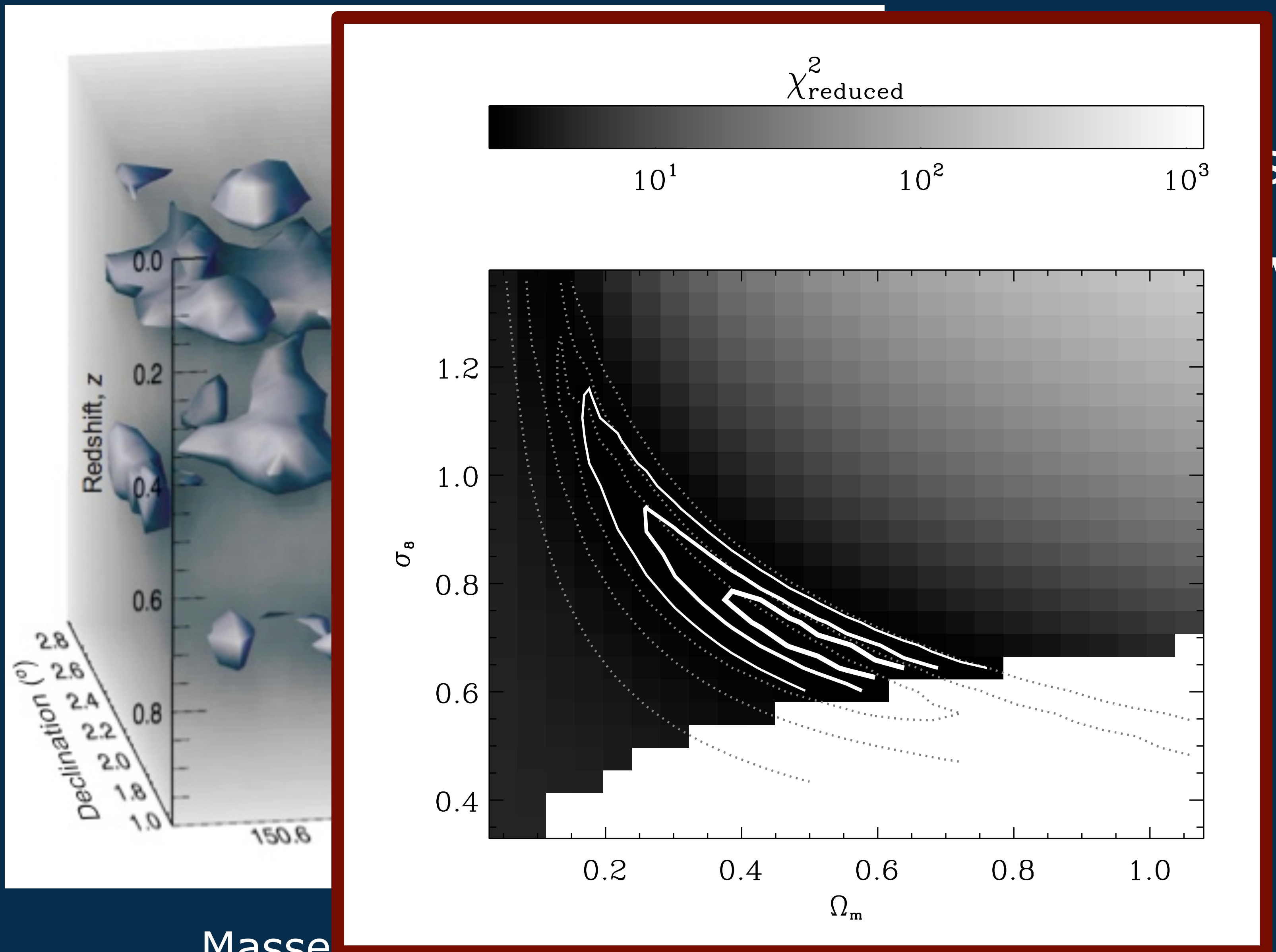


Massey et al. 2007

COSMOS –
2° square survey

- Imaging with ACS I band
- Redshifts from the ground

Dark matter maps



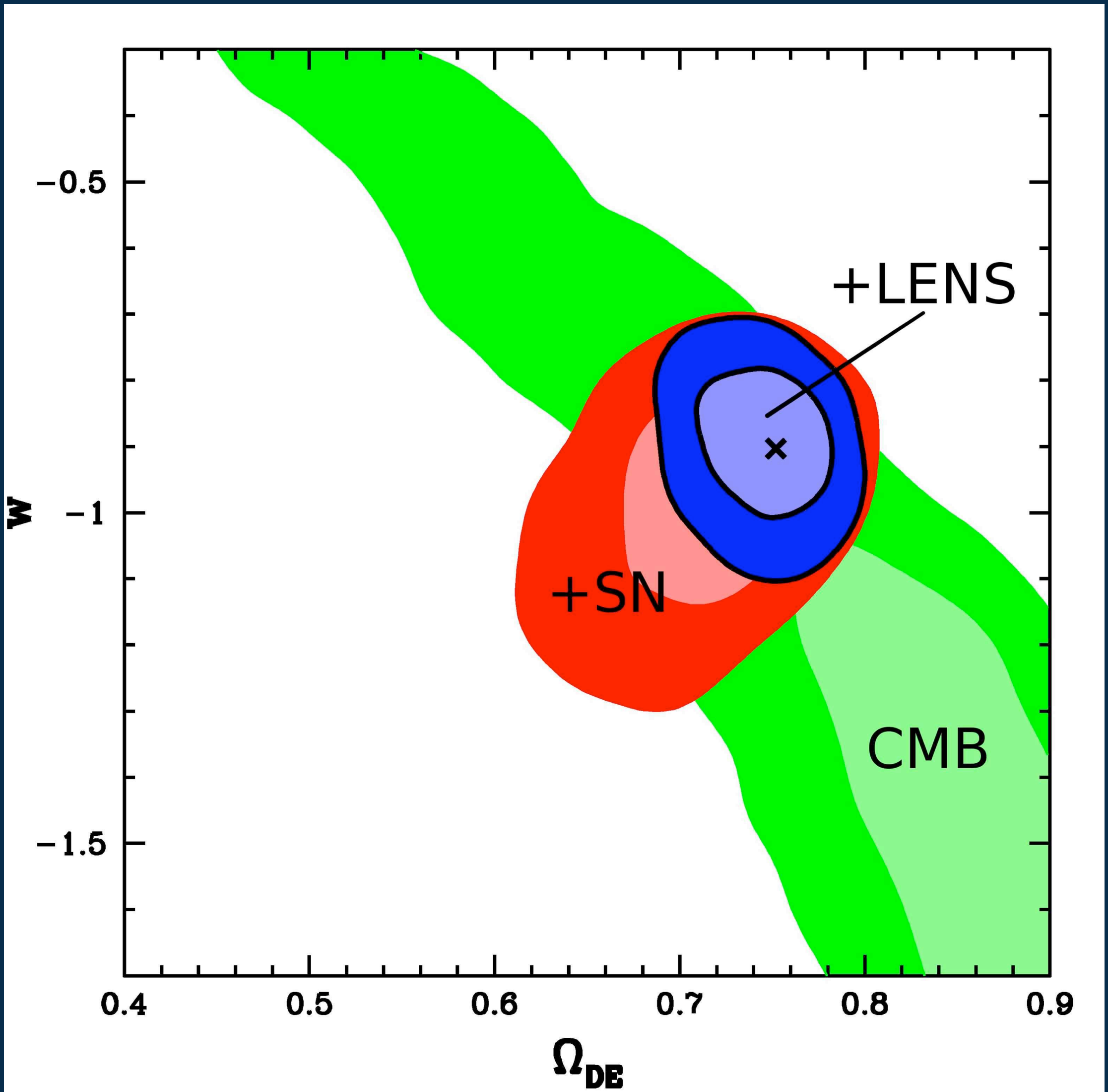
survey

with ACS I

from the

Masse

Dark energy constraints



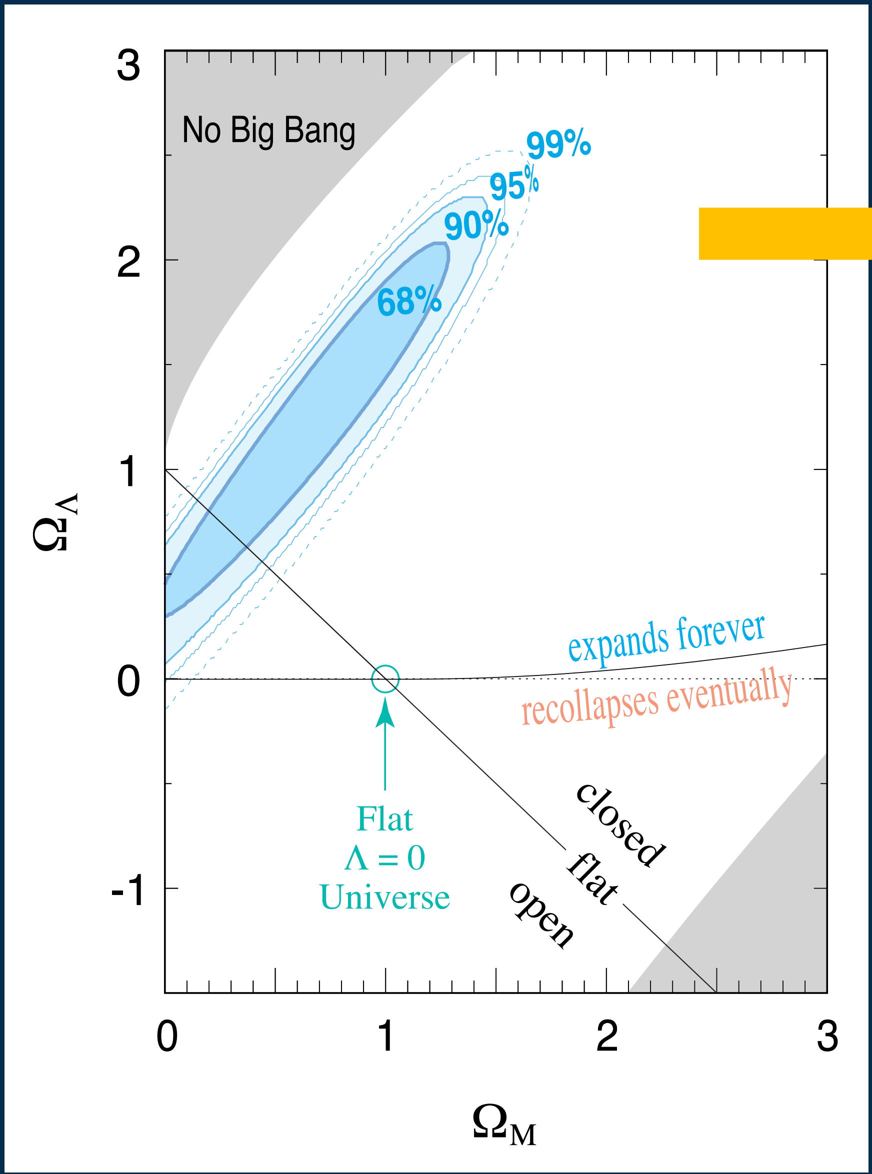
Jarvis et al. 2006 (CTIO)

Dark Energy Task Force: "Weak lensing is potentially the most powerful probe of dark energy. The ultimate limit would be set by the extent to which the systematics can be controlled." (Albrecht et al. 2006)

Can also constrain modifications to General Relativity

Testing GR

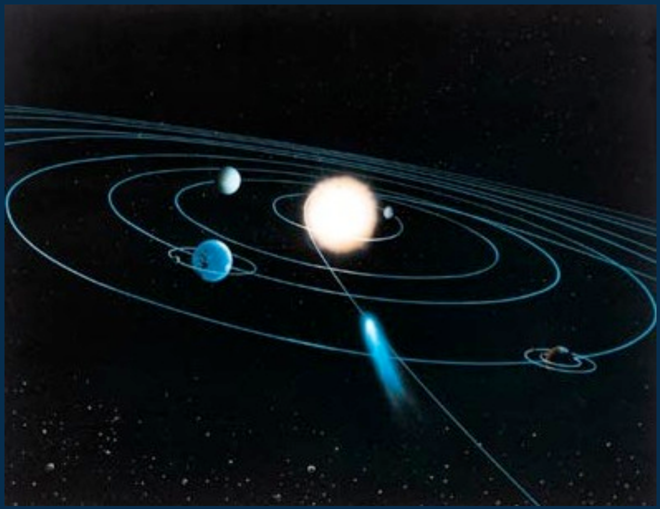
Motivation for modifying GR on large scales



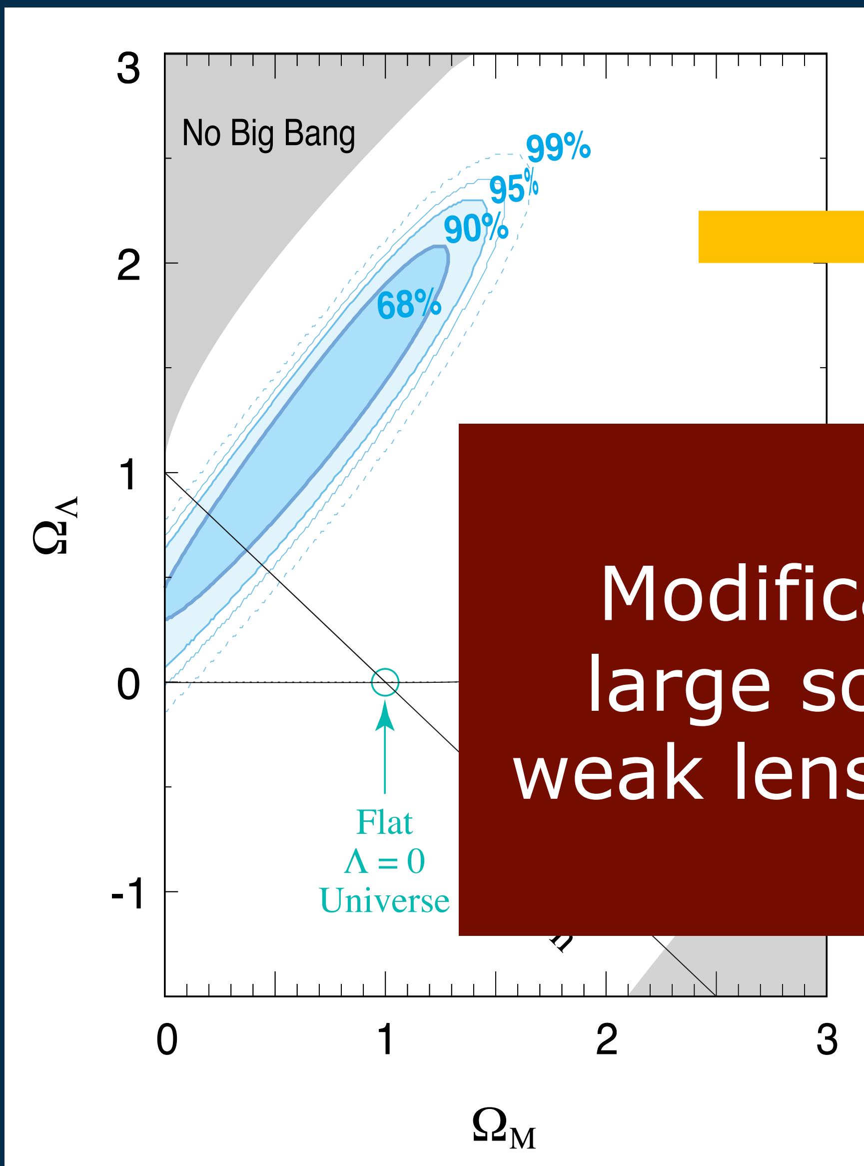
Perlmutter et al. 1999

Accelerated expansion contradicts GR in a matter-dominated universe

But we want to keep gravity the same within the Solar System



Motivation for modifying GR on large scales



Perlmutter et al. 1999

Accelerated expansion contradicts GR in a matter-dominated universe

keep
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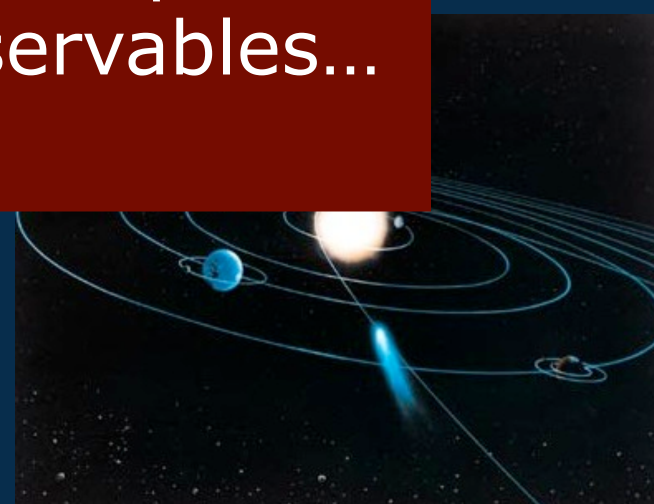
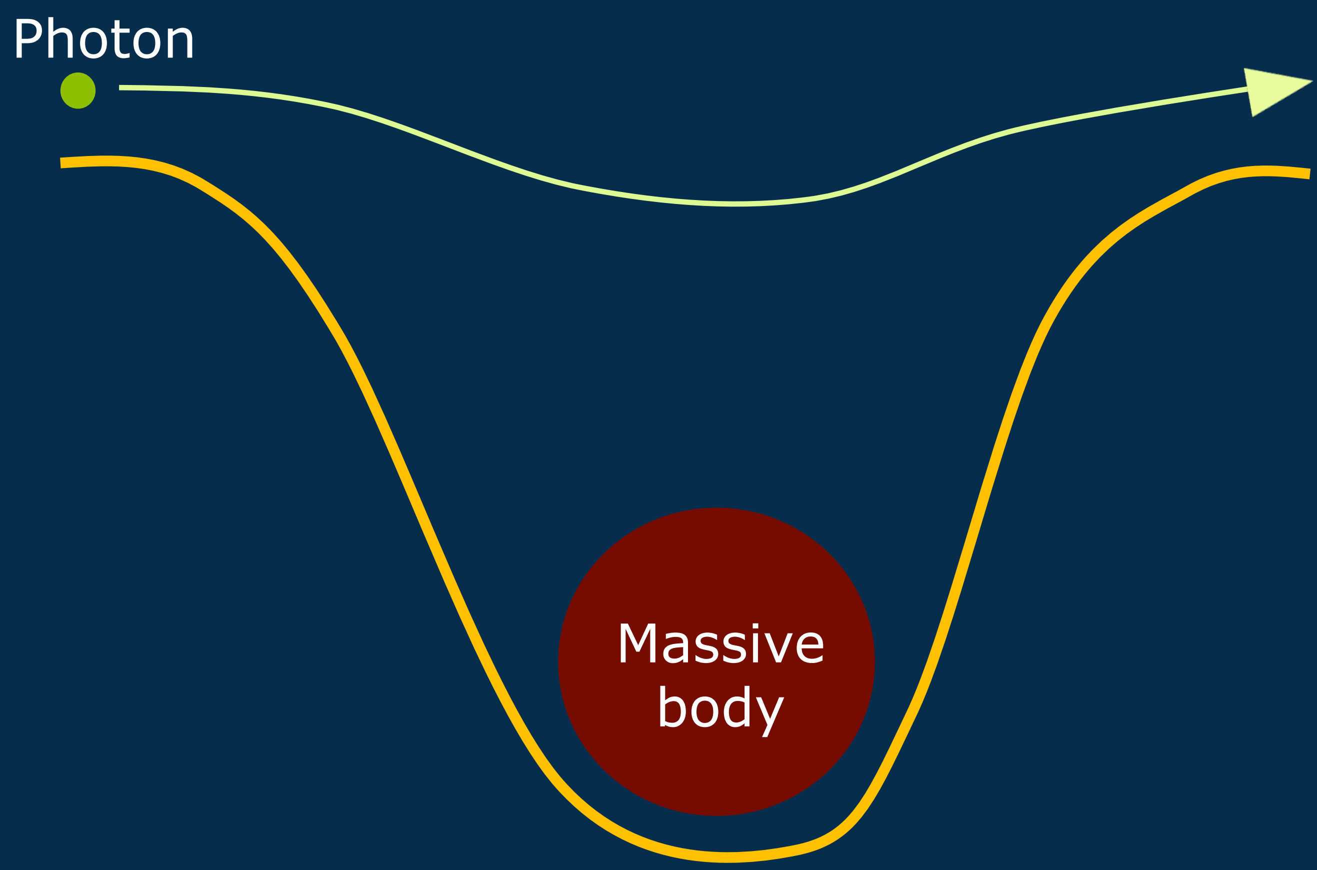


Modifications to GR on large scales will impact weak lensing observables…

Lensing in GR



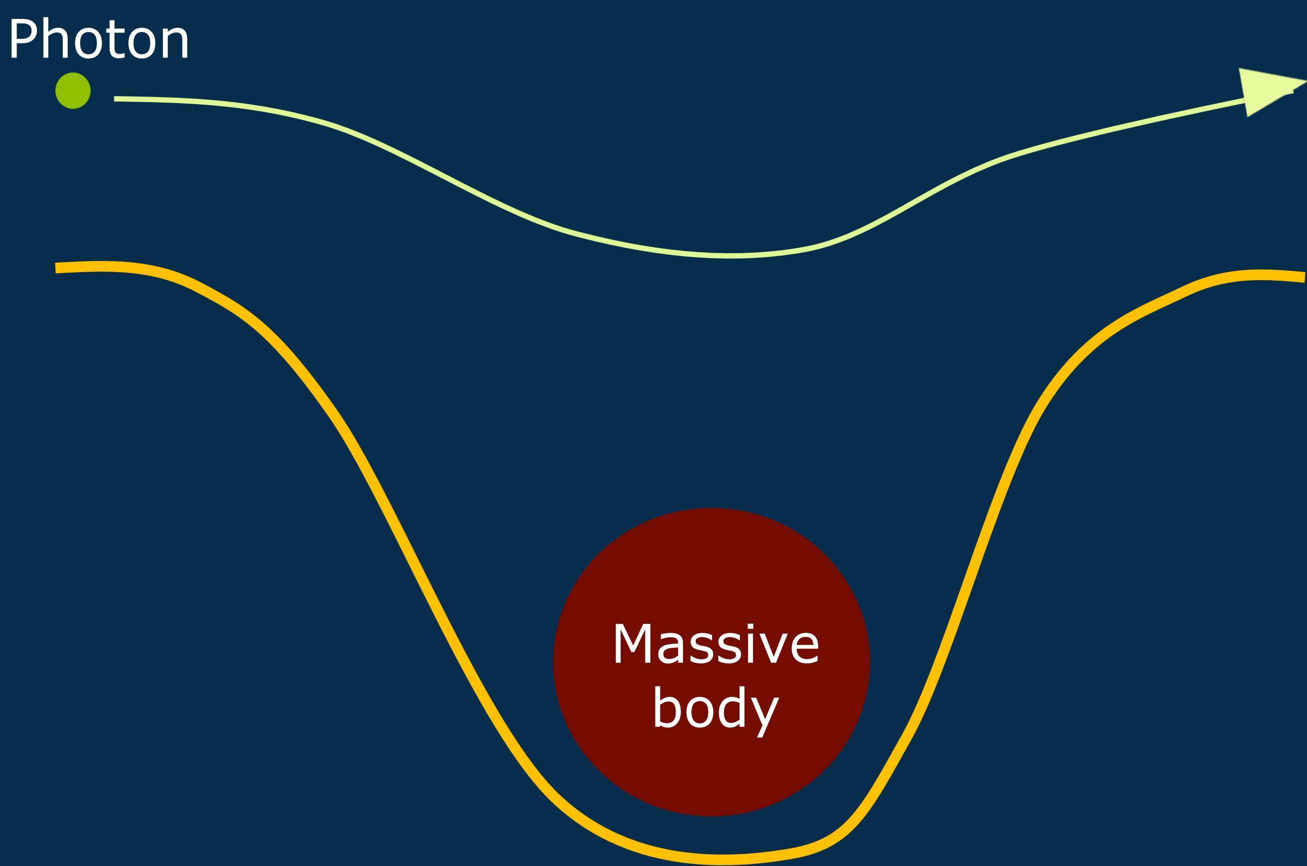
The potential is a function of the matter distribution:

$$\Phi = F(\rho)$$

The light bending angle is a function of this potential:

$$\Theta = G(\Phi)$$

Lensing in modified gravity



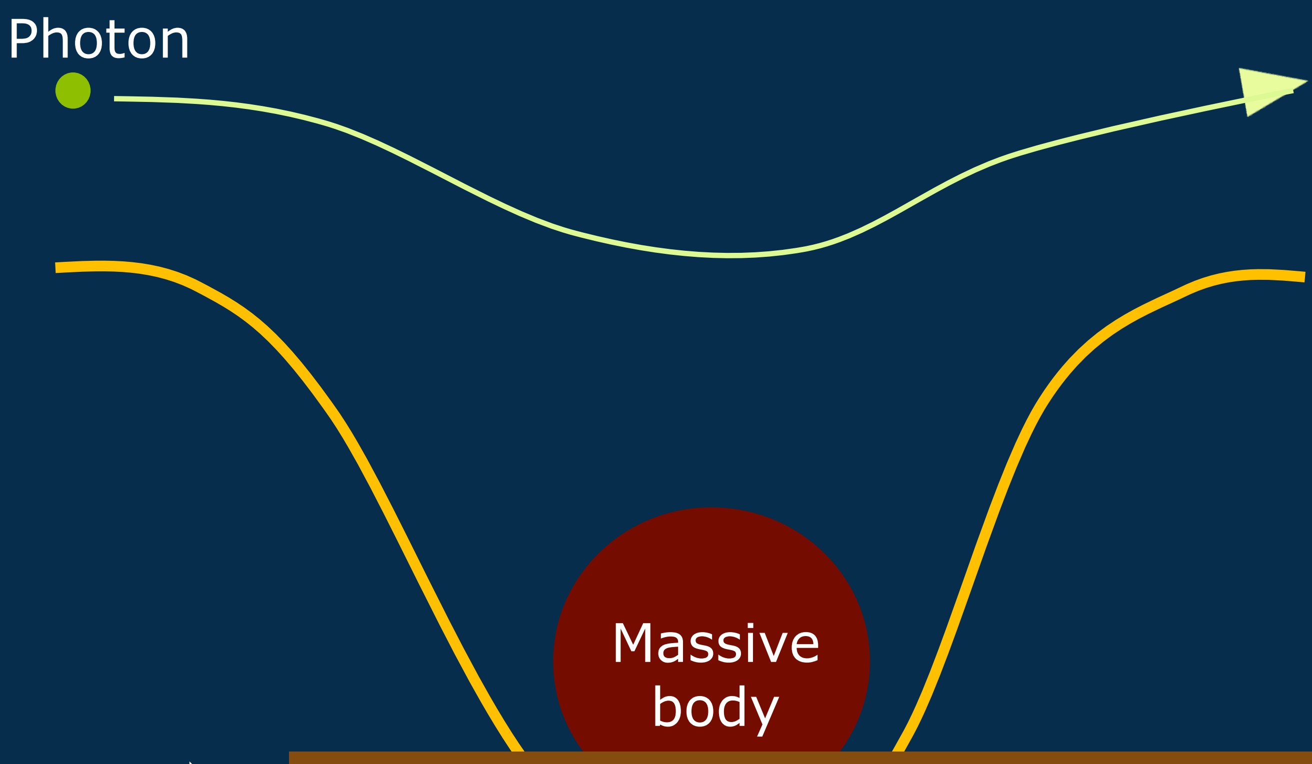
The potential is a function of the matter distribution:

$$\Phi = \overline{F}(\rho)$$

The light bending angle is a function of this potential:

$$\Theta = \overline{G}(\Phi)$$

Lensing in modified gravity



The potential is a function of the matter distribution:

$$\Phi = \bar{F}(\rho)$$

The light bending angle is a function of

$$G(\Phi)$$

Modifying GR can change how:

- matter produces potentials
- photons move in those potentials

Modified gravity theories

- Brans-Dicke
- Tensor-scalar
- Tensor-vector-scalar
- DGP
- Supergravity
- Brane-induced gravity
- Conformal gravity
- F(R)
- F(G)
- Chern-Simons
- MOG
- Torsion gravity
- Massive gravity
- Horava-Lifshitz
- Dilaton gravity
- Goldstone gravity
- Loop quantum gravity
- Discrete quantum gravity
- Effective quantum gravity
- Holographic modified gravity
- Asymmetric brane modified gravity
- Rainbow gravity
- Minimally modified self-dual gravity
- String inspired quintom model

Very large theory space

want model-independent tests of generic deviations from GR

Lessons from "small" scales

The parameterized post-Newtonian (**PPN**) formalism – in the weak-field regime, the gravitational potentials of GR are modified, for instance like:

$$ds^2 = -(1 - 2U + 2\beta U^2)dt^2 + (1 + 2\gamma U + \frac{3}{2}\varepsilon U^2)d\vec{x}^2$$

→ Model-independent constraints on the PPN parameters β, γ, etc.

Can do similar "PPF" expansion about FRW background on cosmological scales

PPN parameters

Parameter	What it measures relative to GR	Value in GR	Value in semi-conservative theories	Value in fully conservative theories
γ	How much space-curvature produced by unit rest mass?	1	γ	γ
β	How much "nonlinearity" in the superposition law for gravity?	1	β	β
ξ	Preferred-location effects?	0	ξ	ξ
α_1	Preferred-frame effects?	0	α_1	0
α_2		0	α_2	0
α_3		0	0	0
α_3	Violation of conservation	0	0	0
ζ_1	of total momentum?	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0

Will 2006

PPN parameters

Parameter	What it measures relative	Value	Value in semi-	Value in fully
γ				
β				
ξ				
α_1				
α_2				
α_3		0	0	0
α				
ζ_1				
ζ_2				
ζ_3				
ζ_4		0	0	0

Solar System constraints:

- Light deflection due to the sun
  $\gamma-1=(-1.7\pm4.5)\times10^{-4}$ (VLBI)
- Perihelion precession of Mercury
  $|2\gamma-\beta-1|<3\times10^{-3}$ (Shapiro 1990)

Are these parameters the same on all scales?

Will 2006

The PPF framework

Method for constraining modified gravity in model-independent fashion (e.g. Hu and Sawicki 2007; Bertschinger & Zukin 2008)

→ Parameters may change depending on time or lengthscale

Important scales:

- Superhorizon – must match expansion history
- Small scales – must match GR
- Intermediate linear regime – important for weak lensing

PPF weak lensing

The metric:

$$ds^2 = a^2(\tau)[-(1-2U+2\beta U^2)d\tau^2 + (1+2\gamma U + \frac{3}{2}\varepsilon U^2)d\vec{x}^2]$$

Standard Newtonian + post-Newtonian scalar potential

Possibly time- and scale-dependent PPF parameters

Goal: to constrain these parameters with lensing data, test GR in the crucial weakly nonlinear regime

Need:

- Post-Newtonian lensing calculation with arbitrary (small) potential U
- A nonlinear study to get beyond γ

Post-post-Newtonian light deflection

We solve for the light ray trajectory, to second order in U and including all nonlinear effects…

From the metric we compute the connection and get the null geodesic equation:

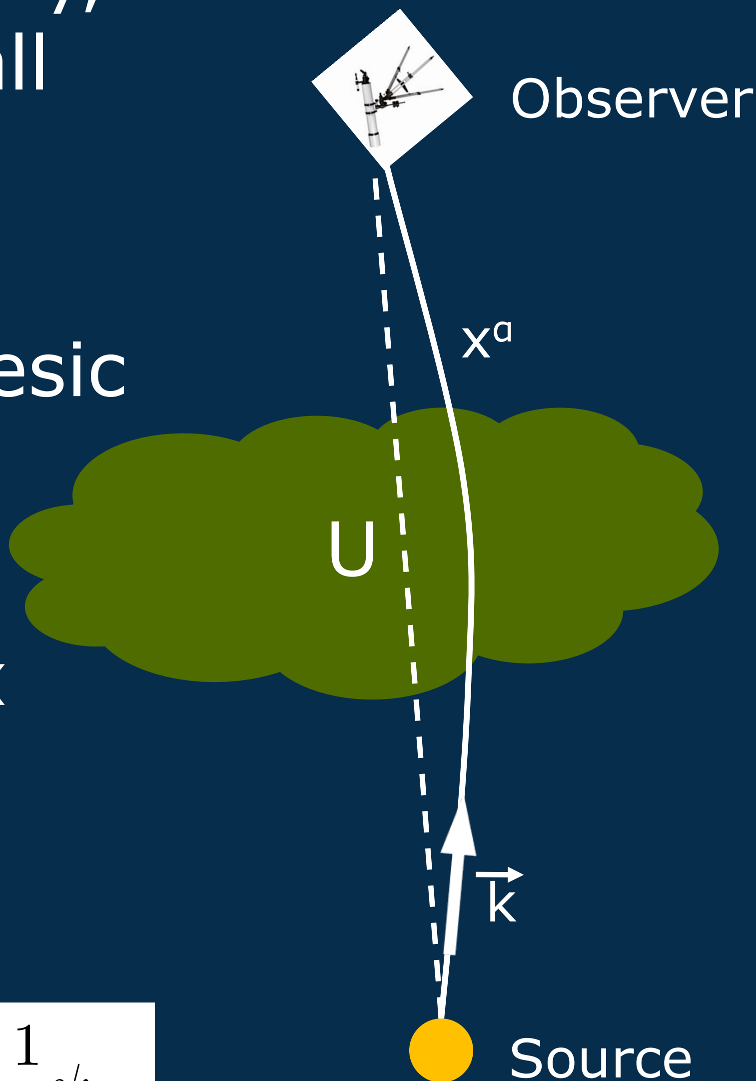
$$\frac{dk^\alpha}{d\lambda} = -\Gamma^\alpha_{\mu\nu} k^\mu k^\nu$$

where $k^\alpha(\lambda) = dx^\alpha / d\lambda$ → Get x

→ get deflection angle α_i

Distortion tensor: $\psi_{ij} = \dfrac{\partial \alpha_i}{\partial \theta^j}$

→ the convergence $\kappa = \dfrac{1}{2}\psi_{ii}$



The convergence

Comoving distance between source and observer

$$\kappa = \int_0^{w} dw' \left(\frac{w - w'}{w}\right) w' \left\{ \left(\frac{1+\gamma}{2}\right) \nabla^2 U \right.$$

The convergence

Comoving distance between source and observer

$$\kappa = \int_0^{w} dw' \underbrace{\left(\frac{w - w'}{w}\right) w'}_{\text{Distance weighting factor}} \left\{ \left(\frac{1+\gamma}{2}\right) \nabla^2 U \right.$$

The convergence

Comoving distance between
source and observer

$$\kappa = \int_0^{w} dw' \; \boxed{\text{Distance weighting factor}} \left\{ \left(\frac{1+\gamma}{2} \right) \boxed{k^2 U} \right.$$

The convergence

Comoving distance between
source and observer

$$\kappa = \int_0^{w} dw' \underbrace{\left(\frac{w-w'}{w}\right) w'}_{\text{Distance weighting factor}} \left\{ \left(\frac{1+\gamma}{2}\right) \underbrace{\nabla^2 U}_{\text{k}^2\text{U}} \right.$$

$$\left. + \left(\frac{6-4\beta+3\epsilon-6\gamma^2}{4}\right)\left[U\nabla^2 U + (\nabla U)^2\right] \right.$$

The convergence

Comoving distance between source and observer

$$\kappa = \int_0^w dw' \left(\frac{w-w'}{w}\right) w' \left\{ \left(\frac{1+\gamma}{2}\right) \nabla^2 U + \left(\frac{6-4\beta+3\epsilon-6\gamma^2}{4}\right) \left[U\nabla^2 U + (\nabla U)^2 \right] \right.$$

Distance weighting factor

k^2U

k^2U^2

The convergence

Comoving distance between source and observer

$$\kappa = \int_0^{w} dw' \; \boxed{\text{Distance weighting factor}} \left\{ \left(\frac{1+\gamma}{2}\right) \boxed{k^2 U} \right.$$

$$+ \left(\frac{6 - 4\beta + 3\epsilon - 6\gamma^2}{4}\right) \boxed{k^2 U^2}$$

$$\left. + \quad \beta\text{-independent second-order terms...} \right\}$$

Linear piece ⟶ constrain γ with power spectrum

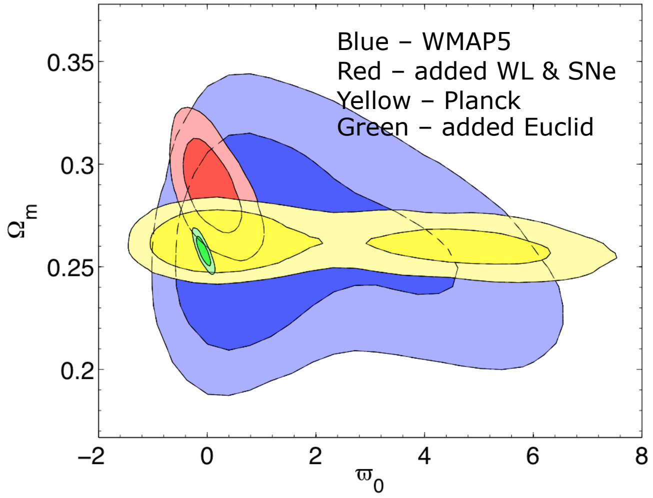
Nonlinear piece ⟶ constrain β with bispectrum

Constraining gamma

$$ds^2 = a^2\left[-\left(1+2\psi\right)d\tau^2 + \left(1-2\phi\right)d\vec{x}^2\right]$$

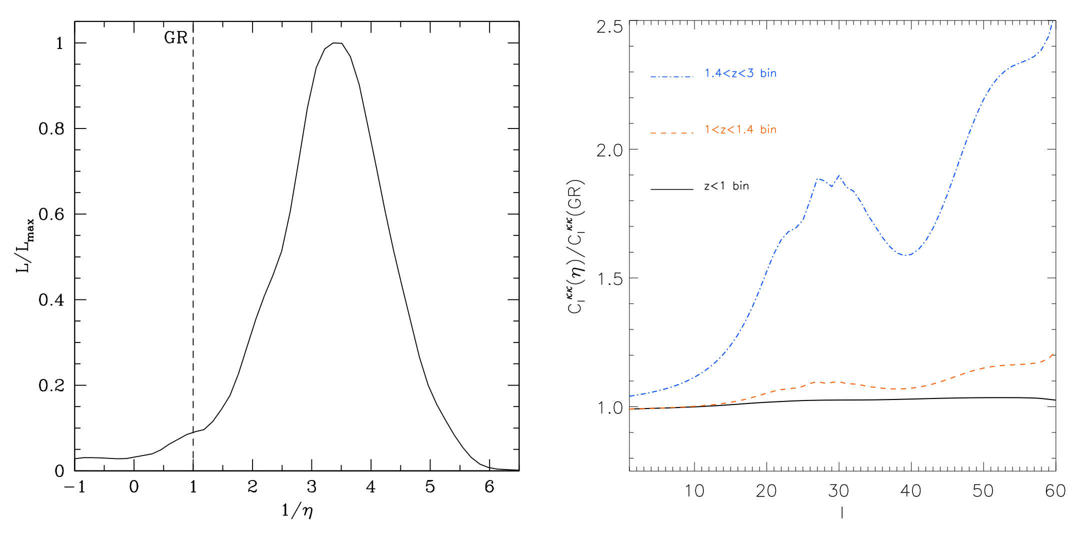
- This talk: $\gamma = \phi/\psi$
- Daniel et al. 2009:

$$\psi = (1+\varpi)\phi$$
$$\varpi(z) = \varpi_0(1+z)^{-3}$$



- Bean 2009:

$$\eta(k,a) = \phi(k,a)/\psi(k,a)$$



Too much shear? DES will do far better with ~2500X more area

Constraining beta and epsilon

Non-GR values for beta and epsilon change the bispectrum…

Recast as a change to an effective f_{NL}:

$$\delta f_{\rm NL} = \frac{3\delta\epsilon - 4\delta\beta}{8}$$

(if we set $\gamma=1$)

ε is generally a function of β, e.g. in scalar-tensor theories (Damour & Esposito-Farese 1996)

See Bergé et al. 2009 for a discussion of weak lensing bispectrum measurements

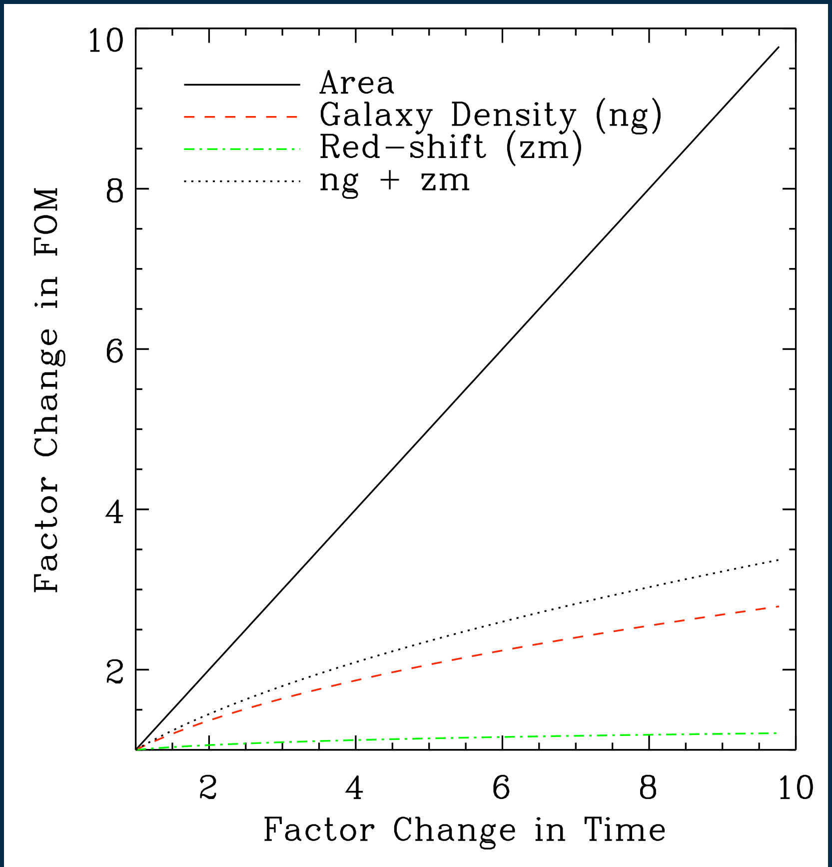
(AV & Caldwell in prep)

The (far) future of weak lensing

Weak lensing requirements

To get accurate shear measurements, we need:

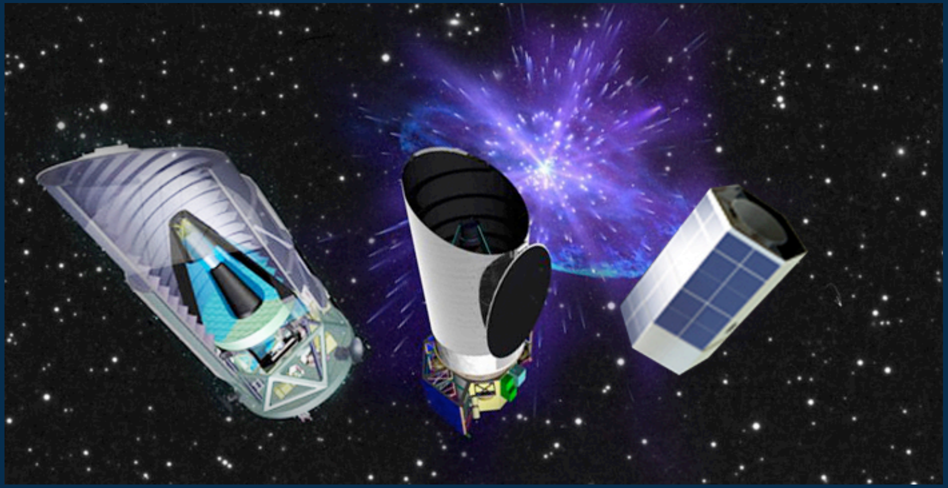
- Accurate galaxy shape measurements
  - Small and stable PSF
  - Low detector systematics
  - Sufficient nearby stars to calibrate the PSF
- Accurate redshifts
- Good statistics
  - Width actually more important then depth for a fixed exposure time



Amara & Refregier 2007

Future possibilities

- NASA/DOE Joint Dark Energy Mission
- ESA Euclid –
  all-sky imaging and spectroscopic survey
- High Altitude Lensing Observatory –
  balloon-borne optical imaging survey



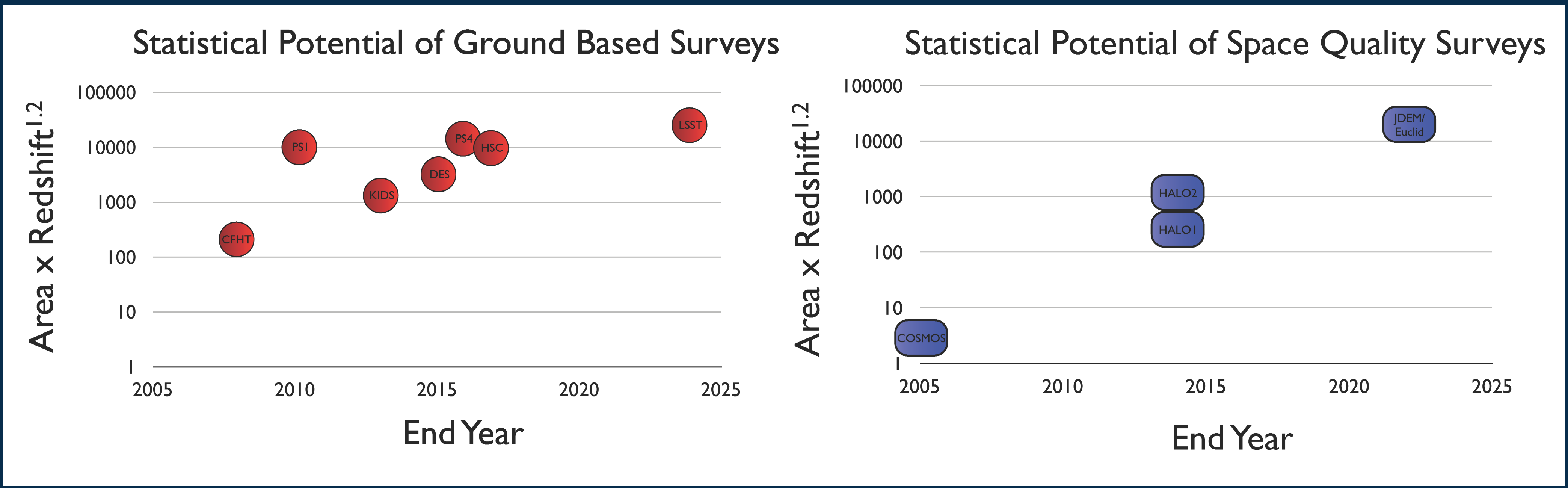
The High Altitude Lensing Observatory

PI: Jason Rhodes

Jeff Booth (JPL), Kurt Liewer (JPL), Michael Seiffert (JPL),Wesley Traub (JPL), Richard Key (JPL), Ali Vanderveld (Caltech/JPL), Adam Amara (ETH Zurich), Richard Ellis (Caltech), Richard Massey (University of Edinburgh), Satoshi Miyazaki (NOAJ Japan), Harry Teplitz (Spitzer Science Center, Caltech), Calvin Barth Netterfield (University of Toronto), Alexandre Refregier (CEA Saclay, Paris), Roger Smith (Caltech)

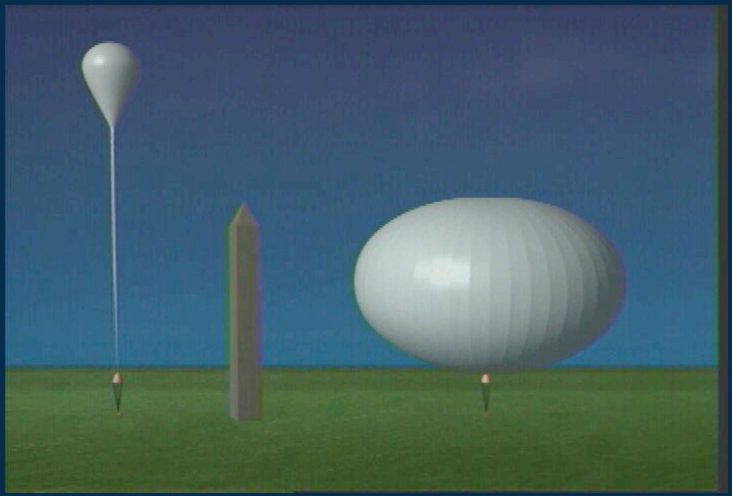
Weak lensing past & future

Higher systematics



Using a balloon

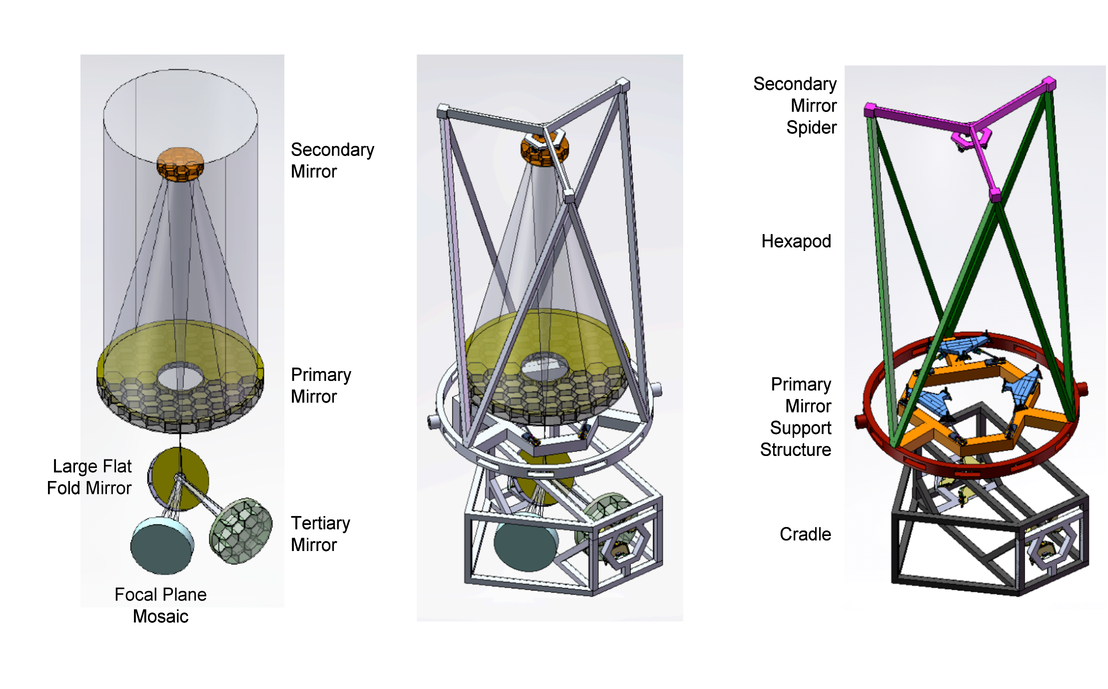
- NASA’s Ultra Long Duration Balloon program
- 7 million cubic foot balloon flown (14 and 22 MCF planned)
- 14 MCF have ~2000 pound payload
- 20 day circumnavigations from Australia baselined for science within a few years



Columbia Scientific Balloon Facility

HALO

- 15-20 day flight Australia to Australia (can stop in South America if needed)
- 1.2m lightweight primary mirror
- 48 2k×4k Hamamatsu CCDs
- Single wide optical filter
- Solar panel to recharge batteries
- 1000 kg

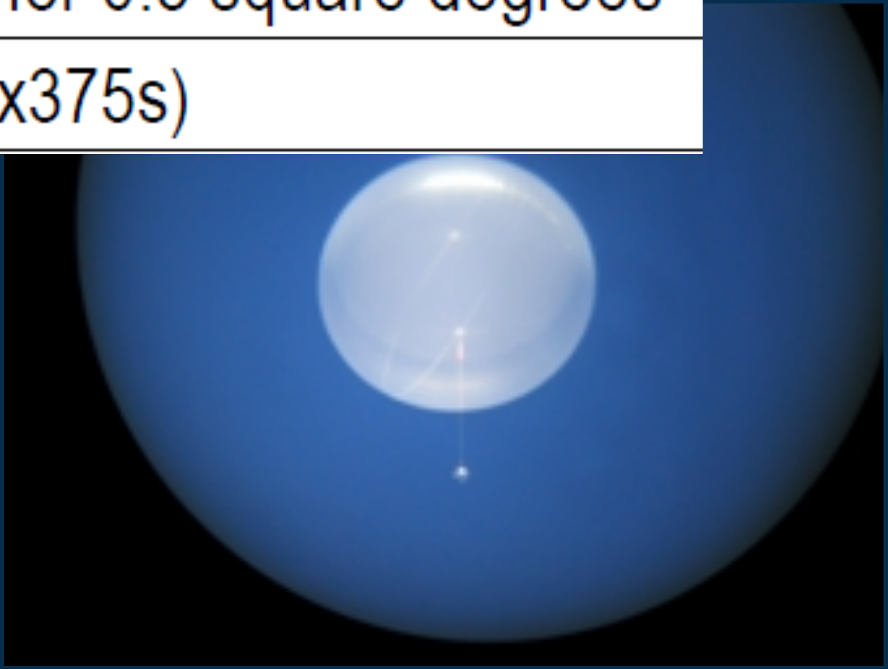


- Need to pick up the disk drives (2 Tb) afterwards to do the science
- Photo zs from ground

Key parameters

Survey area	200+ square degrees
PSF Stability	0.1" RMS with 0.15" pixels
Wavelength coverage	500-720nm
Primary mirror diameter	1.2m
Number of pixels	400Mpix for 0.5 square degrees
Exposure time	1500s (4x375s)

- 15-20 galaxies per square arcminute
- If overlaps with DES area, will provide space-quality calibration sample



Hurdles

Technical:
- Pointing stability to 0.1″ – fast steering mirror
- Thermal stability to 1 K to reach weak lensing shape requirements
- Power requirements of large focal plane
- Mass limit imposed by balloon capabilities

Programmatic:
- Technical requirements imply risk
- High cost relative to typical balloon missions and the balloon budget – external partners
- 14MCF and 22MCF and Australian launch need to be demonstrated

Timeline

March 2010- Proposal due to NASA ROSES/APRA

October 2010- Selections

2010-2011 – Development

2011-2012- Construction

2013 – Integration at JPL

2014- Overnight Test Flight at Ft. Sumner (US)

Late 2014/early 2015- Science flight at Alice Springs, Australia

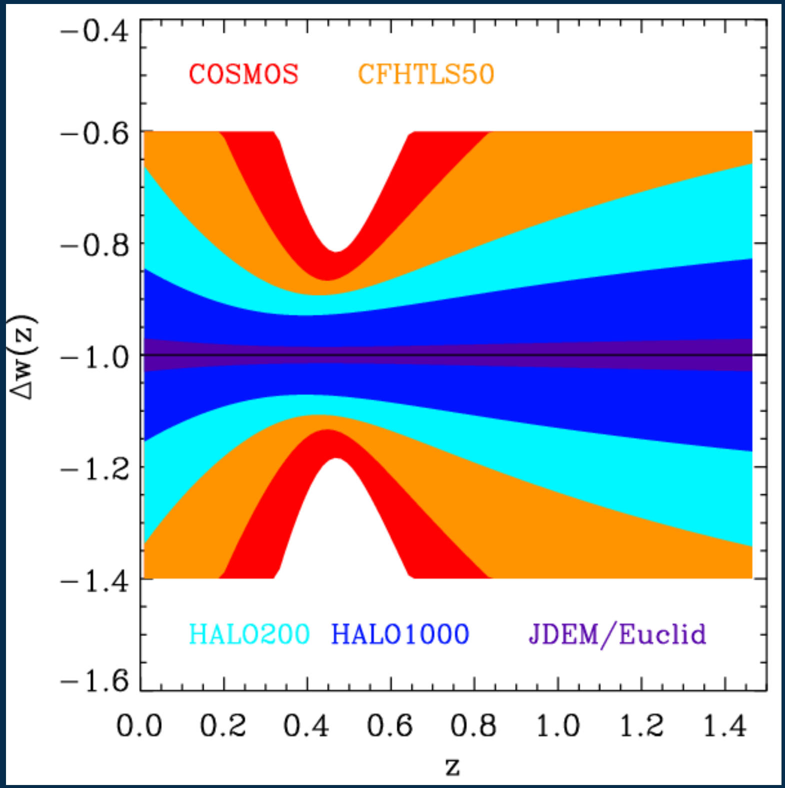
Science reach

Understand dark matter:

- Amount and distribution
- Weak and strong lensing

Explore dark energy and modified gravity:

- Examine expansion history
- Growth of structure



Ancillary science:

- Galaxy morphology and evolution
- Stellar counts
- Surface brightness fluctuations

Conclusions

- Weak gravitational lensing is an excellent cosmological tool
- In particular, it is an excellent probe of modified gravity and dark energy
- The PPF formalism gives model-independent constraints on modifications of General Relativity
- Future space-quality data from HALO can make this possible